

Gamma-Ray Bursts in $1.8 < z < 5.6$ Suggest that the Time Variation of the Dark Energy is Small

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ABSTRACT

We calibrated the peak energy-peak luminosity relation of GRBs (so called Yonetoku relation) using 33 events with the redshift $z < 1.62$ without assuming any cosmological models. The luminosity distances to GRBs are estimated from those of large amount of Type Ia supernovae with $z < 1.755$. This calibrated Yonetoku relation can be used as a new cosmic distance ladder toward higher redshifts. We determined the luminosity distances of 30 GRBs in $1.8 < z < 5.6$ using the calibrated relation and plotted the likelihood contour in $(\Omega_m, \Omega_\Lambda)$ plane. We obtained $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$ for a flat universe. Since our method is free from the circularity problem, we can say that our universe in $1.8 < z < 5.6$ is compatible with the so called concordance cosmological model derived for $z < 1.8$. This suggests that the time variation of the dark energy is small or zero up to $z \sim 6$.

Key words: gamma rays: bursts — gamma rays: observation — cosmology: cosmological parameters

1 INTRODUCTION

There are several distance indicators to determine the cosmological luminosity distance $d_L(z)$. If a certain distance indicator is calibrated without any cosmological models, the indicator can be used to determine the cosmological parameters such as Ω_m , Ω_Λ and $w \equiv p/\rho$. In 1993, Phillips (1993) discovered that the absolute magnitude of Type Ia supernovae at the peak is strongly correlated to the decline rate of the lightcurve after the maximum epoch. This correlation is rigidly calibrated using other distance indicators such as Tully-Fisher and Faber-Jackson relations which are free from any cosmological models. If the correlation does not depend on the redshift z , we can determine $d_L(z)$ only from the observed maximum flux and the redshift of the host galaxy. Since the luminosity distance depends on the cosmological parameters, we can determine them from the estimated luminosity distances for high redshift Type Ia supernovae.

Using the calibrated correlation of Type Ia supernovae, the existence of the dark energy is strongly suggested first by Schmidt et al. (1998); Riess et al. (1998); Perlmutter et al. (1999). Thanks to the latest large number (41) of observations of Type Ia supernovae, the data with $z \leq 1.755$ favor

$(\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$ for a flat cosmology (Riess et al. 2007), which is usually called as the concordance cosmological model. However the most distant Type Ia supernova ever observed is at $z = 1.755$ so that we need either further Type Ia supernovae or other distance indicators to know the property of the dark energy beyond $z > 1.8$, while the anisotropy of the cosmic microwave background (CMB) gives us the information at $z = 1089$ (Spergel et al. 2007).

One of the possible other distance indicators is Gamma-ray bursts (GRBs) whose maximum redshift observed is higher than that of Type Ia supernovae. At present the most distant GRB is at $z = 6.3$ confirmed by the spectroscopic observation with Subaru telescope (Kawai et al. 2006). Since GRBs are known as the most violent and brightest explosion in the universe, they might be a possible good distance indicator beyond $z > 1.8$. For this purpose, in part, several distance indicators have been proposed so far (Fenimore & Ramirez-Ruiz. 2000; Norris et al. 2000; Amati et al. 2002; Yonetoku et al. 2004; Ghirlanda et al. 2004a; Liang & Zhang. 2005; Firmani et al. 2006). Using these distance indicators, the cosmological parameters are independently estimated by several authors such as Ghirlanda et al. (2004b); Firmani et al. (2006) and Schaefer et al. (2007).

However the fundamental difficulty exists when we apply these distance indicators of GRBs to determine the cos-

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mological parameters. At first, these indicators are established assuming the concordance cosmological model. After that, cosmological parameters are estimated by various methods. Therefore the same parameter set would be inevitably obtained. This logic is falling into a circularity problem. Therefore, we should calibrate the distance indicators of GRBs without the theoretical concordance cosmology such as done for the Type Ia supernovae. Then we will suggest that the cosmic distance ladder is extended, and used for the measurement of the cosmological constant.

In 2004, Yonetoku et al. (2004) used 11 GRBs with known redshifts ($0.835 < z < 4.5$) at that time assuming a flat cosmology with $\Omega_m = 0.32$, $\Omega_\Lambda = 0.68$ and $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and derived that the peak luminosity (L_p) of GRBs correlates with the peak energy of the spectrum E_p as $L_p \propto E_p^2$ (so called Yonetoku relation). The chance probability of this correlation is 5×10^{-9} .

In this Letter, using 63 known redshifts of GRBs, we will try to determine the cosmological parameters at higher redshift ($1.8 < z < 5.6$) only with the observable quantities such as the peak flux ($f_{p,obs}$) and the $E_{p,obs}$. Using the luminosity distances of many Type Ia supernovae established without any cosmological models, we will calibrate and reconstruct the Yonetoku relation for nearby 33 GRBs for $z < 1.755$. Applying the calibrated relation to 30 GRBs in $1.8 < z < 5.6$, we determine their luminosity distances as a function of z . Then we will plot the likelihood contour on the $(\Omega_m, \Omega_\Lambda)$ plane and obtain $\Omega_m = 0.37_{-0.11}^{+0.14}$, $\Omega_\Lambda = 0.63_{-0.14}^{+0.11}$ for a flat universe. This method (logic) is very similar to the calibration for Type Ia supernovae with the Tully-Fisher and the Faber-Jackson relations, and it is free from the circularity problem. The essential point is that we use the luminosity distances of Type Ia supernovae like Tully-Fisher relation, which are well determined by the observations and are free from the cosmological models, to calibrate the Yonetoku relation.

In §2 we show how to calibrate the Yonetoku relation using the Type Ia supernovae. In §3 we show the likelihood contour in $(\Omega_m, \Omega_\Lambda)$ plane and argue the cosmological parameters. §4 is devoted to discussions. Throughout the paper, we adopt $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 CALIBRATING YONETOKU RELATION

Generally, the spectrum of the prompt emission of GRBs can be explained as an exponentially connected broken power-law model, so called Band function (Band et al. 1993). We adopted this model to the time averaged gamma-ray spectra of known redshift samples (Yonetoku et al. 2004). Then we can determine a peak energy, E_p , which corresponds to the energy at the maximum flux in νF_ν spectra. Yonetoku et al. (2004) found a strong correlation between the E_p and the 1-second peak luminosity (L_p). Here, we estimate the L_p in $1\text{--}10^4 \text{ keV}$ energy range in the rest frame of GRB. We used the data observed by several independent missions and instruments, so we included appropriate k-correction suggested by Bloom et al. (2001) when we estimate the luminosity for each event. We used 33 GRBs for $z < 1.755$ as the calibration of the $E_p\text{--}L_p$ relation.

We found the empirical formula of the luminosity distance of Type Ia supernovae in Riess et al. (2007) with

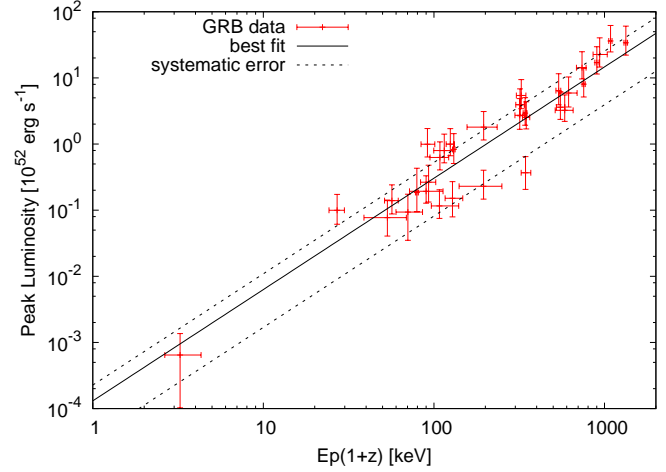


Figure 1. The peak luminosity (L_p) and the peak energy (E_p) in the spectrum of 33 GRBs with $z < 1.62$. The linear correlation coefficient is 0.9478 and the chance probability is 6.0×10^{-17} . The solid line is the best fit curve of $L_p/10^{52} \text{ erg s}^{-1} = 1.31 \times 10^{-4} [E_p(1+z)/1 \text{ keV}]^{1.68}$ while two dashed lines are the curves including the systematic error. See text for details.

$0.359 < z < 1.755$ as

$$\frac{d_L(z)}{10^{27} \text{ cm}} = 14.57 \times z^{1.02} + 7.16 \times z^{1.76}. \quad (1)$$

This formula agrees with the real data within a relative error of 1 %. Here we note that this formula is not unique and the other formula is possible. What is important here is that we do not assume any cosmological models at this stage but simply assume that the Type Ia supernovae are the standard candle for $0.359 < z < 1.755$ irrespective of the cosmological model. We apply this formula to 33 GRBs with the redshift $z < 1.62$ in our sample to obtain $L_p = 4\pi d_L(z)^2 f_{p,obs}$ while $E_p = (1+z)E_{p,obs}$. In figure 1, we show the calibrated $E_p\text{--}L_p$ relation for 33 GRBs within $z < 1.62$. The linear correlation coefficient is 0.9478 and the chance probability is 6.12×10^{-17} . We tried to find the best fit curve in the form as

$$\left(\frac{L_p}{10^{52} \text{ erg s}^{-1}}\right) = (1.31 \pm 0.67) \times 10^{-4} \left(\frac{E_p}{1 \text{ keV}}\right)^{1.68 \pm 0.09} \quad (2)$$

In this equation, the error is expressed as the statistical uncertainty. However the data distribution has a larger deviation around the best fit line compared with the expected Gaussian distribution. We estimated this systematic deviation in the normalization as 9.57×10^{-5} . The solid line is the best fit curve and two dashed lines are the curves including the systematic error in the normalization.

3 COSMOLOGICAL PARAMETERS

At present, there are more than 100 GRBs with known redshift, but the E_p has not been measured for all GRBs. Moreover the calibrated range in figure 1 is $3.3 \leq E_p \leq 1333 \text{ keV}$ in the rest frame of GRBs, so we should use GRBs within this range to estimate the luminosity distance of $z > 1.755$. Although we know the redshift of GRB 050904 is $z = 6.3$, its peak energy is reported as $E_p \sim 3 \text{ MeV}$. This is out of our calibration, so we exclude it from our sample. Then, we apply the calibrated Yonetoku relation to 30 GRBs in

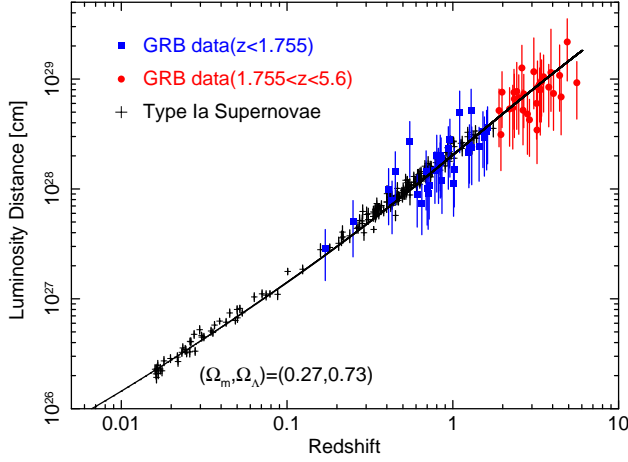


Figure 2. The luminosity distance as a function of the redshift measured by the calibrated E_p - L_p relation. The blue and the red points are the luminosity distance of $z \leq 1.755$ and $z > 1.755$, respectively. The data of Type Ia supernovae are also plotted as the black cross points. The uncertainty bar of each point includes the systematic dispersion around the best fit line of figure 1. For the purpose of easy comparison, a solid line of the concordance model is also drawn.

$1.8 < z < 5.6$ to determine the luminosity distance as a function of z . In figure 2 we show the luminosity distance of 33+30 GRBs as a function of the redshift. The blue and the red points are the luminosity distance of $z \leq 1.755$ and $z > 1.755$, respectively. The uncertainty bar of each red point includes the systematic dispersion around the best fit line of figure 1

For each GRB with $z = z^i$ we have the observed peak flux ($f_{p,obs}^i$) in the unit of $\text{erg cm}^{-2}\text{s}^{-1}$ and the observed $E_{p,obs}^i$ in the unit of 1 keV. Then using the equation 2, the luminosity distance can be derived as

$$d_L(z^i) = 10^{24} \text{cm} \sqrt{\frac{1.31}{4\pi f_{p,obs}^i}} [E_{p,obs}^i (1+z^i)]^{1.68/2}. \quad (3)$$

In the ΛCDM -cosmology with $\Omega_k \equiv \Omega_m + \Omega_\Lambda - 1$, the luminosity distance is given by

$$d_L^{th}(z, \Omega_m, \Omega_\Lambda) = \begin{cases} \frac{c}{H_0 \sqrt{\Omega_k}} \sin(\sqrt{\Omega_k} F(z)) & \text{if } \Omega_k > 0 \\ \frac{c}{H_0 \sqrt{-\Omega_k}} \sinh(\sqrt{-\Omega_k} F(z)) & \text{if } \Omega_k < 0 \\ \frac{c}{H_0} F(z) & \text{if } \Omega_k = 0 \end{cases} \quad (4)$$

$$\text{where } F(z) = \int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda - \Omega_k(1+z)^2}}.$$

We define a likelihood function as

$$\Delta\chi^2 = \sum_{i=1}^{30} \left(\frac{\log d_L(z^i) - \log d_L^{th}(z^i, \Omega_m, \Omega_\Lambda)}{\Delta d_L(z^i)} \right)^2 - \chi_{best}^2. \quad (6)$$

Here χ_{best}^2 means the chi-square value for the best fit parameter set of Ω_m and Ω_Λ . In figure 3 we show the contour of the likelihood $\Delta\chi^2$ for the luminosity distances of 30 GRBs in $1.8 < z < 5.6$. Compared with the case of Type Ia supernovae, the shape of the probability contour stands vertical since the luminosity distance strongly depends on Ω_m rather than Ω_Λ for higher redshift samples. This is clear from the functional form of $F(z)$. Without any prior the most likelihood value is $(\Omega_m, \Omega_\Lambda) =$

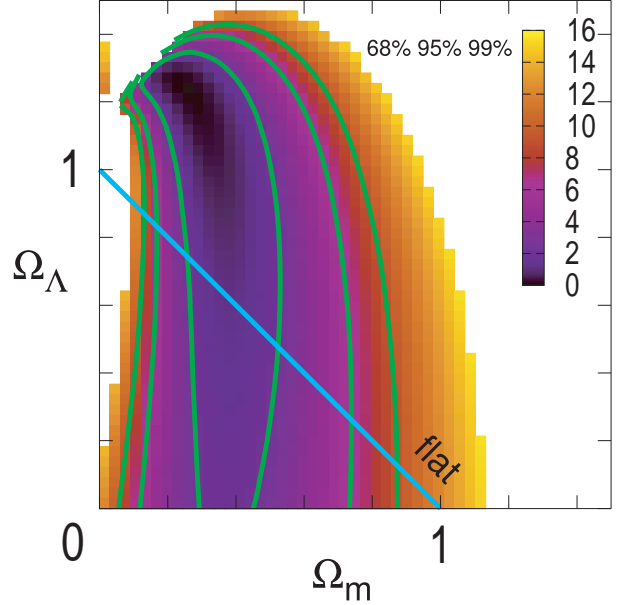


Figure 3. The contour of the likelihood $\Delta\chi^2$ (see equation 6) for the luminosity distances of 30 GRBs in $1.8 < z < 5.6$. The significance levels of 68%, 95% and 99% are also shown on the same panel. Compared with the case of Type Ia supernovae, the shape of the contour stands vertical since the mean redshift is much larger. The most likelihood value of cosmological parameters are $(\Omega_m, \Omega_\Lambda) = (0.25^{+0.27}_{-0.14}, 1.25^{+0.10}_{-1.25})$ while for a flat cosmology prior they are $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$.

$(0.25^{+0.27}_{-0.14}, 1.25^{+0.10}_{-1.25})$ while for a flat cosmology prior that is $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$ with 1σ uncertainty.

In figure 4, we show the same contour as figure 3 but for the luminosity distances of 16 GRBs in $3 < z < 5.6$. The shape of the contour stands more vertical than fig. 3, which should be so. Without any prior the most likelihood values of cosmological parameters are $(\Omega_m, \Omega_\Lambda) = (0.33^{+0.52}_{-0.26}, 1.14^{+0.21}_{-1.14})$ while for a flat cosmology prior they are $(\Omega_m, \Omega_\Lambda) = (0.49^{+0.33}_{-0.24}, 0.53^{+0.22}_{-0.37})$. We see for a flat cosmology the value of $(\Omega_m, \Omega_\Lambda)$ for higher redshift samples is compatible with that for whole samples if we take the error into account.

4 DISCUSSIONS

- (5) In this Letter we extended the cosmic distance ladder using GRBs calibrated by Type Ia supernovae, and argued the cosmological parameters using only the GRBs in $1.8 < z < 5.6$ except for a flat cosmology prior. Since our region of $1.8 < z < 5.6$ has not been explored yet, this is the first report to estimate the cosmological parameters up to $z = 5.6$. It is possible to combine our data with (1) Type Ia supernova, (2) CMB, (3) Baryon Acoustic Oscillation (4) the large scale structure measurement and (5) weak gravitational lensing, to constrain the $w(z) \equiv p/\rho$ parameter of the equation of state for the dark energy (Tsutsui et al.).

The calibrated Yonetoku relation has a large dispersion in the normalization which is mainly caused by the systematic error. Therefore, currently, the measurement of the luminosity distance is not so accurate compared with the other distance indicators such as Type Ia supernova. It

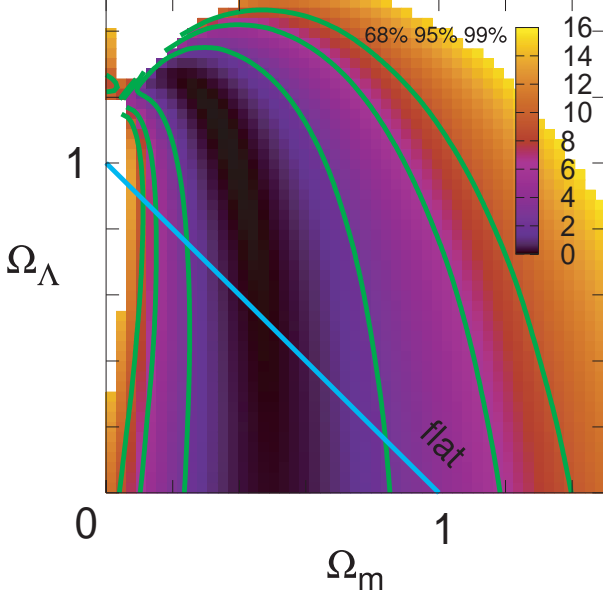


Figure 4. The same as fig. 3 but for the luminosity distances of 16 GRBs in $3 < z < 5.6$. The shape of the contour stands more vertical than fig. 2. The most likelihood values are $(\Omega_m, \Omega_\Lambda) = (0.33^{+0.52}_{-0.26}, 1.14^{+0.21}_{-1.14})$ while for a flat cosmology prior they are $(\Omega_m, \Omega_\Lambda) = (0.49^{+0.33}_{-0.24}, 0.53^{+0.22}_{-0.37})$.

may be difficult to discuss the detailed time history of the cosmological parameters yet. However, if this deviation is the intrinsic property of GRBs, we will be able to discover the hidden physical quantities, or distinguish a possible subclass from entire population of GRBs like Type Ia supernova. These improvements in the cosmic distance ladder will lead us to explore the deep space with better accuracy in near future.

As for the Amati-relation (Amati et al. 2002) which relates the total isotropic energy to E_p , possible selection bias effects and evolution effects are claimed (Li 2007; Butler et al. 2007) while Willingale et al. (2007) argues against such effects. It is important to check possible selection bias and evolution effects in the Yonetoku relation also. Tanabe et al. (2008) examined the evolution effect as well as the observational selection bias assuming the concordance cosmology, and found that they are quite small. We think that the selection bias and evolution effects are not larger than the systematic uncertainty in the normalization of the calibrated Yonetoku relation, although we agree that further examinations are required.

Theoretical models of dark energy are reviewed, for example, in a recent paper by Frieman, Turner & Huterer (2008). In some models such as scalar field models, dark energy looks like the cosmological constant for low redshift $z < 2$ but not for high $z > 2$. Therefore the estimate of the cosmological parameters for $z > 2$ is important either to refute or confirm such models. Our present result for $1.8 < z < 5.6$ gives $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$ for a flat cosmology prior while Type Ia supernova for $z < 1.755$

does $(\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$ (Riess et al. (2007)), which means that $(\Omega_m, \Omega_\Lambda)$ for $z < 1.8$ and for $1.8 < z < 5.6$ are the same within the 1 *sigma* statistical error. This suggests that $(\Omega_m, \Omega_\Lambda)$ did not change so much from $z = 5.6$ to $z = 0$ so that such a scalar field model should look like the cosmological constant up to $z \sim 6$ at least.

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